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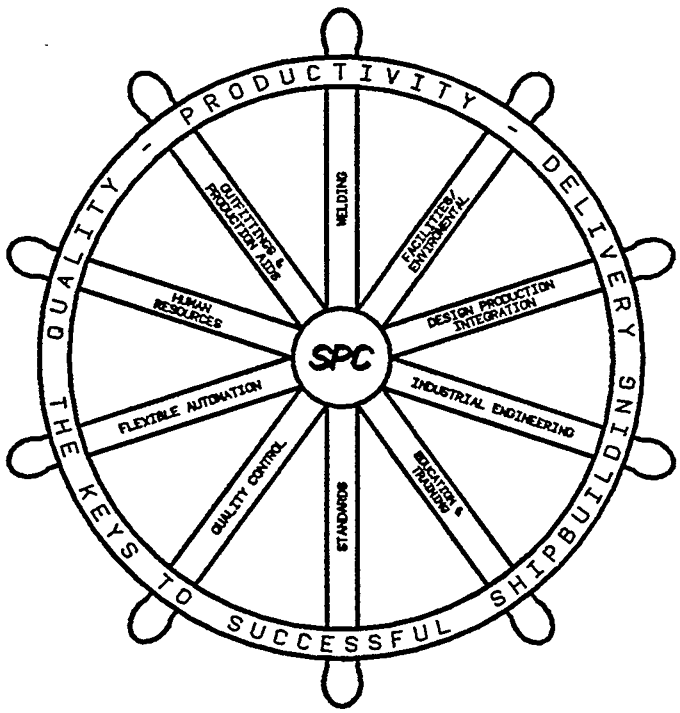

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Laser Welding Analysis and Experiments

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ABSTRACT

A "Seamless Engineering" approach for mechanical design and laser welding manufacturing combines a method for welding analysis with a method for stress analysis through the development of radiant heating models for use in a nonlinear finite element computer program.

Experiments were performed welding steel plates, using a five-axis Computer Numerical Controlled (CNC) work station to translate welding specimens under a 5-kilowatt $C0_2$ laser. Thermocouples installed near the weld seam were used to measure the transient temperature field during welding. The measured temperatures were compared to the analytical predictions, and the welds were sectioned so that predictions of properties in the heat-affected zone could be compared with experimental data.

This paper presents analytical results using classical methods of analysis and includes solutions for temperature fields, heating and cooling rates, and metallurgical properties in heat affected zones.

INTRODUCTION

Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), Finite Element Method (FEM), Virtual Reality (vR), Numerical Control (NC), CNC, Computer-Aided Inspection (CAI), and Cornputer-Aided Machining/Computer-Aided Manufacturing (CAM): These are the approaches to design and manufacturing that will propel the United States into preeminence in the 21st century global economy. These technologies emerged in the 1980's and now permeate most of the design process in naval weapons, launchers, and ships. America has led the way.

If our competitiveness in the next century can be assured, it will be through applications of computers to the demands of the marketplace through these technologies.

In the area of naval weapons, the most significant pioneering application of the FEM was the design of the MK 104 dual thrust rocket motor (DTRM) for the SM-2 Block 11 Standard Missile (1 and 2). This was followed by design of the Block IV missile, which employs a separate booster motor. For Block IV, detailed FEMs were used for designing the rocket motors, fins, and a thermal protection system for aerodynamic heating.

In missile launcher design, the MK 26 Guided Missile Launching System (GM LS) arrived too soon to benefit from a FEM stress analysis. However, the launcher was even tually modeled to improve the system's ability to withstand underwater shock. The MK 41 Vertical Launching System (VLS) was modeled very early in the design process to meet underwater shock requirements. The FEM was used extensively in the design of the VLS canister for Block IV. The most significant advance was the mathematically coupled analysis and concurrent design of both the canister and the missile. In both the missile and launcher areas, the design process and manufacturing processes are also making extensive use of computer-aided design and drafting (CADD).

In the area of shipbuilding, large FEMs with many thousands of degrees of freedom were used in the mechanical design of the Spruance Class Destroyer (DD 963). The DDG 51 class design was a milestone in that all aspects of the design process were done with CAD, such as drawing generation, analysis, information management, configuration control, and interference detection.

A stress analysis for the aft deck house (3) was completed using the database and the FEM. The structural design of the TAGOS-19 Small Waterplane Area Twin Hull (SWATH) ship was completed with the FEM (4). The twin hull presented challenging design problems resulting from prying, shear, and torsional loads not present in monohulls. Furthermore, TAGOS-19 class ships are now being built from drawings in a numerical database. Extensive use of VIVID®,1 a computer program that allows an architectural "walk through" of a ship using virtual reality, was used in the arrangement of the Sea *Wolf* submarine.

In the same time period in which the CAD and FEM technologies emerged, CNC machining and robotics became commonplace on shop floors throughout the world. Boeing and Giddings & Lewis are now building 777 aircraft wings, four at a time, on a CINC workstation 88 m (290 ft) long, 21 m (70 ft) wide, and 2-1/2 stories high (5).

The next frontiers of computer-based engineering are nicknamed "concument" and "seamless." Concurrent means the simultaneous application of computers to several areas of the development process. For example, in order to minimize the time taken between the emergence of a concept and the introduction of the item to the marketplace, the design team includes production engineers so that the most producible and least expensive product results.

Some concurrent processes do not involve drawings on paper; for example, in the design of a pump and impeller (6), the internal geometry was determined through fluid flow calculations in a geometrical database in a CAD system. When the geometrical design was complete, another computer generated tool paths for a CNC mill that manufactured the parts; paper drawings were not used at either stage. Finally, rather than a dimensional inspection of the parts to assure conformance to drawings, the "as built" geometry was determined by measurement probes on a CAI station. The "as built" geometrical data were used as input to a final fluid dynamics calculation to see if the pump using the manufactured parts would meet performance criteria; again, drawings were not required. This smooth passage from step to step in design, development, and manufacturing, using a shared database at each step, is the essence of "seamless" engineering.

This paper describes a two-year effort at the Naval Surface Warfare Center Dahlgren Division (NSWCDD) to build a "seamless" technology for designing steel parts for assembly by means of laser welding with CNC workstations. The FEM is used in the stress analysis during design and to guide the final material selection and thickness. The same finite element computer database and software is then used to design the manufacturing process; i.e., laser beam on-off schedule, beam power, speed of welding, and tool paths. Just as stress analysis and post processing provides the mechanical designer with a visual representation of the stress field, the heat transfer analysis provides a means for visualizing the heat affected zone, metallurgy, and manufacturing process. The focus of the study has been on parts of sizes commonly found in missiles and launchers, which are compatible with the power available from the laser and the capacity of the five-axis NC workstation. However, with additional effort, the technical approach could also be applied on a larger scale to shipbuilding.

Three technical sections follow. The first technical section discusses classical, closed form analysis of the laser welding process and prediction of material properties. The next section discusses modeling the laser welding process with the FEM. The third technical section discusses the experiments conducted to determine effective thermophysical properties and to verify the accuracy of the welding process calculations. Finally, some potential applications of the laser welding process are shown in missile, launcher, and ship design.

1 Developed and owned by Newport News Shipbuilding

CLASSICAL MATHEMATICAL SOLUTION

The basic closed form mathematical model of the laser welding process is based on the "Rosenthal line source model." The solution was discovered by Rosenthal (7) in 1946. The model assumes a uniform line source of heat moving at constant speed in a thin plate. The moving line is perpendicular to the plane of the plate (when viewed from above, the line source looks like a point moving on the surface of the plate). When expressing the source strength in terms of laser power and absorptivity at the date,the formula is

$$T(x, y, t) = T_o + \frac{AI}{2\pi hk} e^{-\frac{v}{2a}(x-vt)} K_o\left(\frac{v}{2a}\sqrt{(x-vt)^2+y^2}\right) \quad (1)$$

where

- T_o = initial plate temperature (c)
- A = absorptivity
- I = laser power(W)
- h = plate thickness (m)
- k = thermal conductivity (W/m K)
- v = beam travel speed (m/s)
- a = thermal diffusivity (m^ 2/s)
- x = distance in direction of beam travel (m)
- Y = distance from weld centerline (m)
- t = time (s)
- K_o = modified Bessel function of the second kind

Here it is assumed that the thermophysical quantities *k* and a do not vary with temperature. The plate is infinite in extent, and the speed of welding, v, is constant. The plate thickness and the intensity are constant. The resulting solution is pseudostationary, i.e., the temperature field always looks the same to an observer moving at speed v with the laser beam. The solution is mathematically mgorous, and the Bessel function can be evaluated with high precision; however, if there are significant violations of any of the above assumptions, results must be used cautiously. In general, the Rosenthal solution has been found to be very valuable in understanding the welding process it was used as a starting point in designing simple processes and as a check for finite element calculations.

The classical Rosenthal solution has recently become more useful due to advances in computer methods. Figure 1 is a temperature plot obtained by loading the Rosenthal solution into a commercial software package. The operator can readily change any of the parameters in the basic formula and can manipulate the object to provide any view desired.

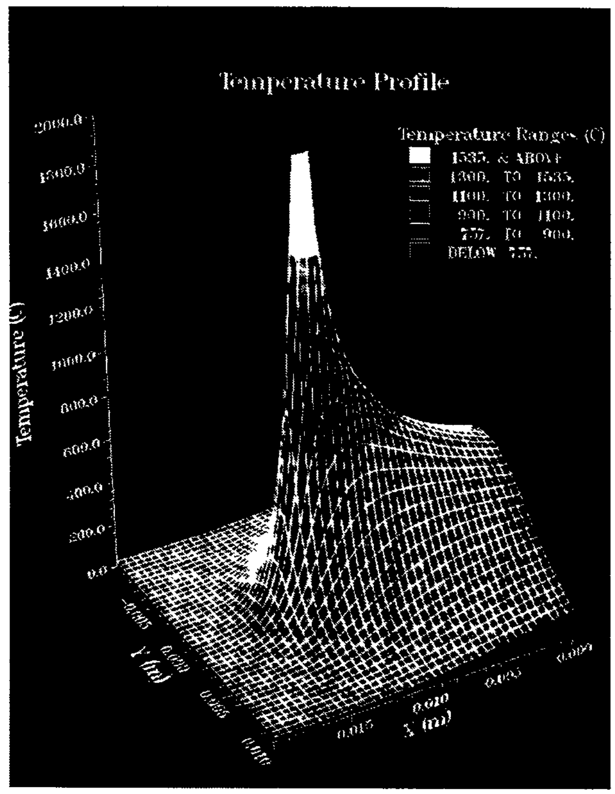


Figure 1. Temperature profile

Heating and cooling rates, important to metallurgy, can be obtained by differentiating Equation (1) with respect to time. Figure 2 is a plot of the heating rate. The heating rate is highest directly in front of the beam and lowest (large negative values, indicating cooling) immediately behind the beam.

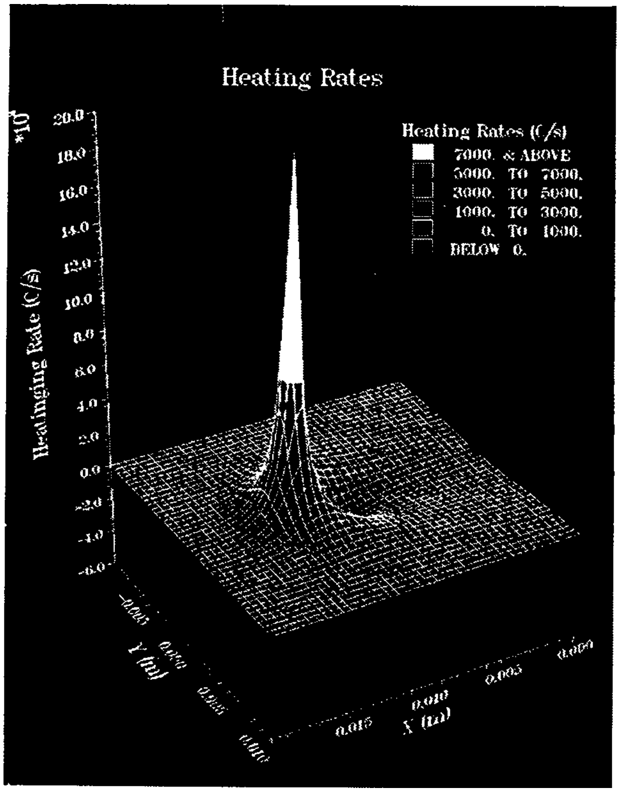


Figure 2. Heating rate plot

The computer calculus program "Mathematical" was used to differentiate Equation (1) with respect to the spatial coordinates to construct the temperature gradient field. The resulting formulas for the gradient field involve additional Bessel functions (the chain and product rules applied to Equation (1) produce large messy formulas). The gradient field of Equation (1) is the heat flux vector and shows the direction of heat flow away from the weld. A plot of the gradient field is shown in Figure 3. There is a tendency for crystal growth along the gradient field lines, which allows a computer prediction of the microstructural orientation in the fusion zone.

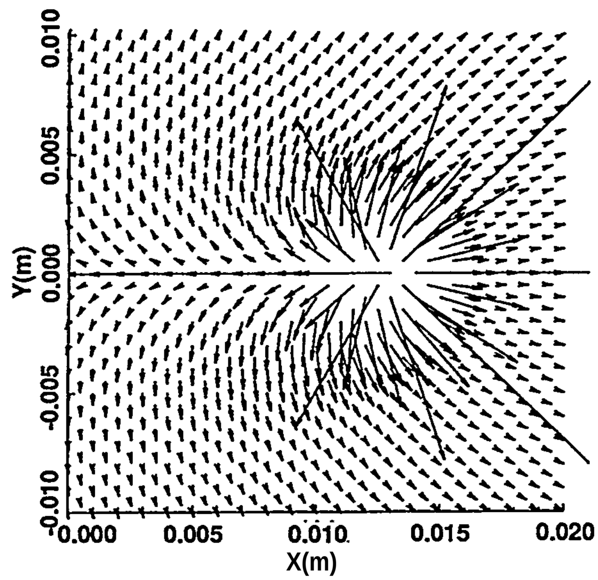


Figure 3. Thermal gradient vector field

Hardness and yield strength for laser welding of steel can be predicted using the above computer analyses to generate a set of temperature-versus-time plots for points of interest in the material. The analysis follows the approach of Metzbower (8). The "carbon equivalent" for the material is first computed from the formula,

$$Ceq = \%C + \%Mn/6 + (\%Cr + \%Mo + \%V)/5 + (\%Cu + \%Ni)/15 \quad (2)$$

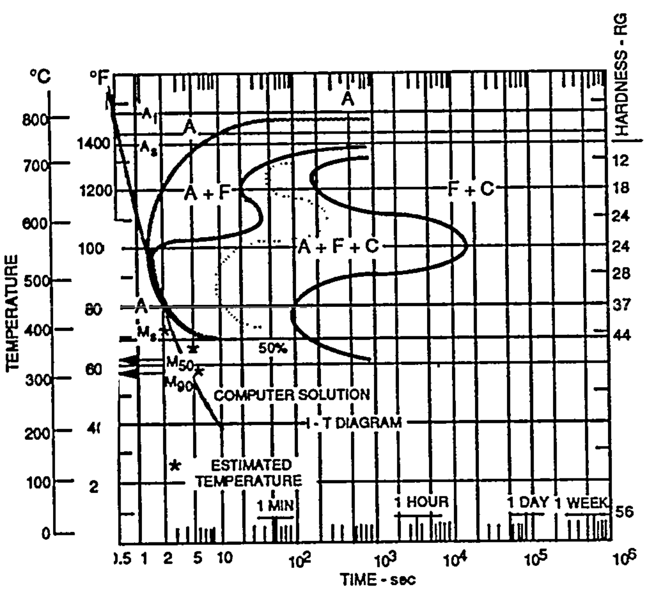
Here the alloy elements symbols have the usual meanings. The volume fractions of Martensite, Bainite, and ferrite/pearlite are then given by

$$\begin{aligned} Vm &= 1 - \exp\{-0.69' [St/Stm]^2\} \\ Vb &= 1 - \exp\{-0.69^* [St/Stb]^2\} \\ Vfp &= 1 - Vm - Vb \end{aligned} \quad (3)$$

Where St is the time it takes at the point of interest to cool from 800°C to 500°C, and the half times for Bainite and Martensite to transform, S_{tb} and S_{tm}, are computed from

$$\log(S_{tb}) = 8.84\,Ceq - 0.74$$
$$\log(S_{tm}) = 8.79\,Ceq - 1.52 \qquad (4)$$

Figure 4 is an overlay of a temperature-versus-time computer solution plotted on an Aerospace Metals Handbook I-T diagram. The I-T diagram gives a qualitative prediction of the crystalline structure, and the computer calculations with the above formulae give a precise quantitative prediction of the metallurgy. Additional formulae are available for predicting the yield stress and hardness, once the metallurgy is known.



TEMPERATURE vs TIME

PEAK TEMPERATURE:	1535.0 C
DIST FROM WELD CENTERLINE:	0.081 cm
BEAM INTENSITY:	2000.0 W
ABSORBTIVITY:	50.0%
PLATE THICKNESS:	0.32 cm
WELDING VELOCITY:	1.06 cm/sec
PREHEAT TEMPERATURE:	22.2 C

Figure 4. Temperature vs time overlay

In summary, given the assumptions of constant material properties, thickness, speed of welding, and beam power, the above formulae allow prediction of the temperature field during welding, the resulting metallurgy, and other material properties required for design. The calculations are quick and inexpensive on modern computers equipped with the proper software.

FINITE ELEMENT ANALYSIS (FEA)

This section discusses the FEM approach to laser welding. The finite element approach is an alternative that has the potential to overcome all of the limitations of the above classical method for real materials and variable geometries. Furthermore, the finite element method has the ability to use the same numerical database as the stress analysis and computer drafting of the final design.

The analytical solution described previously is only valid under the following restrictions

1. Infinite flat 2-dimensional (2-D) domain
2. Constant negligible thickness
3. Constant material properties (no spatial or temperature dependence)
4. Constant velocity source
5. Straight line weld path

These limitations greatly restrict the solution's utility for practical application to typical welding operations. Other analytical solutions are possible, using various moving sources based on a singularity integral approach, which may remove some of the stated restrictions. In general, all of the resulting formulations provide point solutions that require fairly expensive special function evaluations at each material point for each time at which temperature is desired. As a result of this expense, a numerical approach was sought that would provide the full simulation required to optimize the welding process, while still remaining cost and time effective.

Simple analyses were carried out using a finite difference thermal network formulation – a transtinite element formulation in which the conduction solution was obtained in the Laplace domain and then inversely transformed to provide the temperature-time history and a more general finite element solution using the ABAQUS™ program. A decision was made to perform the remainder of history and a more general finite element solution using the ABAQUS™ program. A decision was made to perform the remainder of the simulations using this FEM program, based on its already widespread availability throughout the Navy, its generality for stress-displacement analyses as well as thermal analyses, and its high level of integration within the overall CAD/ CAE/CAM process.

This approach allowed for modeling complex 3-D simulations with variable beam speed and spot size; curved welds; and temperature dependent material properties, thus eliminating nearly all of the restrictions described earlier. The identification of the proper temperature dependent material properties presents a considerable challenge, however. Also, the severe spatial and temporal non-linearities produced when using variable thermal properties significantly reduce the integration step size, and greatly increases the cost of the analysis. Therefore, a methodology (described below) was developed to obtain a representative set of constant properties based on the specifics (thickness and diffusivity) of the problem being solved. Also, while this approach permits the inclusion of radiation and both free and forced convection (i. e., resulting from shielding gas flow); it also greatly complicates the analysis. For the example cited here, these effects were ignored.

The process of using a CAD system through analysis modeling and simulation to validate a weld process specification, along with some lessons learned, is described below. The typical process involved the use of Pro-Engineer” as a design modeler. The geometry of the problem was then transferred to PATRAN, a modeling program, for stress and thermal analysis. This generally involved subdividing the design-modeler derived surfaces to control mesh density and to define weld path, followed by the generation of hyperpatches to describe the volume of the structure. Then by proper manipulation of the meshing controls, a finely graded mesh is produced. Figure 5 illustrates such a mesh.

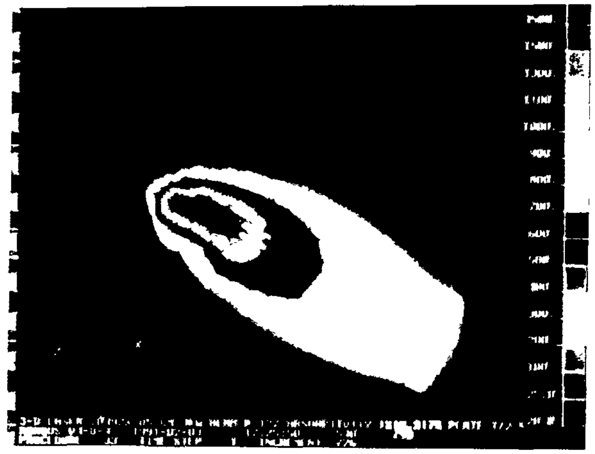


Figure 5. Finite element solution for a source moving along the surface of a weld specimen

Several observations can be made to point out lessons learned regarding the compromise between solution accuracy and cost. In a few early calculations with 2-D shell models, with through-thickness integration points, great efficiency and acceptable accuracy were obtained. However, the elements were found to be incompatible with some of the post-processing and stress analysis functions. (The mesh shown in Figure 5 is composed of DC3D8 linear hexahedral elements.) Several rules of thumb were developed to guide in meshing. One of these rules is that symmetry or no-flux boundaries need to be exploited. Also, for the power and speed settings typical of laser welding processes, it was found that in the direction transverse to the weld path, a mesh dimension of approximately two weld thicknesses was sufficient to approximate an isothermal boundary.

The model shown simulates a constant power butt weld pass on a 25.4 mm (l-in.) square by 9.5-mm (0.375 -in.) thick flat plate. Here the far lateral edge is 12.7 mm (0.5 in.) from the weld, which results in approximately a 5°C (41°F) temperature increase. The mesh should be highly graded from a fairly refined uniform mesh in the vicinity of the weld to a very course mesh at the lateral boundary. In this example, the small element dimension is chosen as a cube with a face area equal to the area of the laser beam spot size. The symmetry condition at the weld line results in this element being split in half; this split cube is element being split in half; this split cube is repeated laterally one step, followed by the full cube, and then the grading is carried out to produce one element through the thickness at the isothermal boundary.

A fair degree of judgment and expedience is used to arrive at a “good looking” mesh. This mesh is then swept along the weld path to produce a full 3-D model. For butt welds on thin, topologically uniform 2-D structures (i.e., flat, cylindrical, etc.), a no-flux or symmetry boundary condition can be assumed at the weld line even though the geometry is not symmetrical. Thus, the two sides of the weld can be analyzed separately. In actual practice, it is often only necessary to analyze one side of the weld.

For branched structures (i.e., T welds), all sides of a structure must be modeled. When filler metal is not used, the problem can be greatly simplified by allowing the mesh to be connected even before the beam has passed. In most cases, this actually produces surprisingly small error. A characteristic element face area equal to beam spot area is chosen to simplify the specification of the energy incident on the weld zone and the propagation of the beam along the weld path. The critical feature is that the mesh is invariant and regular along the weld. After higher resolution meshes were investigated, it was concluded that the approach described above provided a good compromise between accuracy and computer costs.

The thermal input is applied as a surface heat flux on the row of elements adjacent to the weld path. The magnitude of the heat flux is obtained by assuming the beam power is uniformly distributed on the beam spot, and that the absorptivity is invariant with temperature. These approximations and the distortion of the energy distribution into a square greatly simplified the problem specification without introducing significant error. The actual energy distribution is annular; however, detailed simulations showed that for a dynamic welding pass, the energy could be uniformly smeared over a square with area equal to the beam area. Figure 5, shown previously, exhibits a finite element solution for a source moving along the surface of a weld specimen, Figure 6 shows the temperature at various positions on the material.

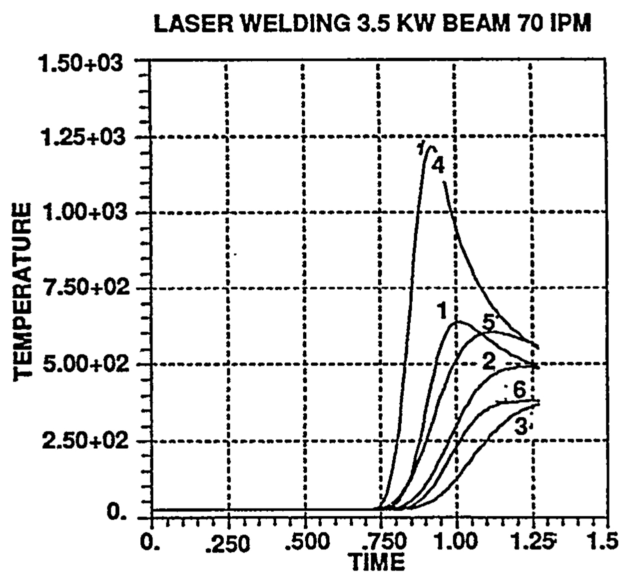


Figure 6. Temperature at various positions on the material

The numerical value of the absorptivity can be approximately calculated from the Stefan-Boltzman constant times the emissivity times the equivalent beam temperature to the fourth power, divided by the laser power setting.

$$A = \sigma \varepsilon T^4 / I \qquad (5)$$

A more practical empirical approach based on a simple calibration test will be described below.

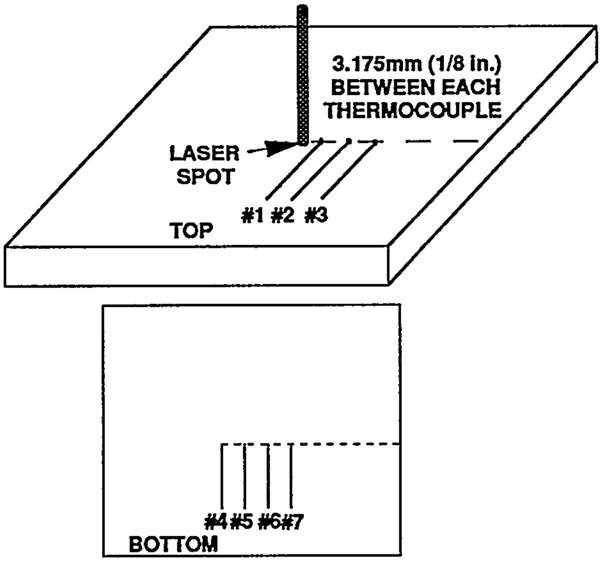
To simulate the beam motion, a schedule of heat flux is derived for each element such that it rises from zero, when the edge of the beam is projected to first enter the element domain, to its maximum value, when the spot is centered on the element, and then falls to zero when the spot edge exits the element. The adjacent elements are heated in a consistent manner such that the total heat flux to the structure is constant, and a particular element exposure is twice the time it takes the beam to traverse the characteristic element dimension. Beam speed can be varied by altering this traversal time as a function of time; also, beam power can be varied to simulate beam defocusing, which is used to reduce incident energy when required to avoid burn-throughs.

This approach provides direct analogs to the process parameters used by a manufacturing engineer when constructing a CNC program: namely, beam path, beam speed, and standoff (when standoff equals the focal length for full power incident on the focused spot area). The simulation results are then studied to predict maximum temperatures, back face temperatures, fusion zone, heat-affected zone (HAZ), metallurgical phases, and hardness variations. These functions are provided as post-processing options and can be visualized using the modeling program as fringe plots or time histories. Computer generated animations can also be videotaped to provide a level of data abstraction and fusion that is helpful in developing a “feel” for the welding process. With this type of feedback, a manufacturing engineer can vary parameters in the process schedule in a systematic fashion. Additional simulations provide further feedback, which makes it possible to quickly arrive at the final process.

The technique described above provides a straightforward method to accurately simulate laser butt welds (without filler metal or gas shielding), heating, heat treating, and cutting. Analyses involving other weld geometries, forced convection due to shielding gas flow and filled welds, are somewhat more complicated; however, the FEM provides sufficient generality to adequately handle these complications. Filler metal can be added in a conceptually straightforward manner through the use of the user element capability.

As the complexity of the simulation increases, difficulty in correlating the analysis to the experiment increases. This is as much an effect of the proliferation of unknown (unknowable) parameters in the problem as it is the complexity of the physics being modeled. The final test is in how effective the computer simulation aids a manufacturing engineer in developing a process specification. In practice, most of the tasks presented can be modeled adequately as a straightforward conduction problem, neglecting much of the complicating physics, as long as one or two empirical variations are run for calibration purposes. These empirical runs are made on small representative coupons of the correct material and thickness. This eliminates the risk of damaging expensive, few-of-a-kind, complex components or overheating pyrotechnic ordnance. Once a validated process specification has been developed, welds can be made with high confidence and safety.

A fairly rigorous calibration procedure was developed as a formalization of this coupon testing. A specimen of the parent material was instrumented with seven thermocouples radiating from its center at distances of 1, 2, and 3 beam diameters on the top, and 0, 1, 2, and 3 beam diameters on the bottom (Figure 7). The plate was then heated by a square wave pulse of laser energy directed at the center of the top surface for a predetermined duration and power setting. Once the plate cooled, exposure was repeated with a different power setting or different duration. Data collected from several tests were analyzed by a nonlinear least squares method to fit a closed-form singularity integral solution. Model parameters obtained were then proven out by a detailed FEM simulation of the experiment.



#4: DIRECTLY BELOW BEAM SPOT

LASER POWER: 500W
PULSE DURATIONS: 1,2, AND 4 sec

Figure 7. Thermocouple placement

This system identification procedure provides approximate estimates of the physical parameters required for the simplified FEM described above. Essentially, it is a process of linearizing the analysis for a temperature range of interest, which may be dependent on the intent of the analysis. The parameters could also be chosen so that the error is minimized in some least squares fashion over the entire domain. A solution of this type would over-predict peak temperature somewhat, but would have lower error at the far field. The choice of approach must be based on the desired end result.

For HAZ or fusion zone predictions, the error should be minimized for the temperature range and distance scale expected. For peak backface temperature predictions, the model should be tuned differently. A different analysis run is required for each model change, but the aggregate run times are still much less than the full nonlinear analysis. The temperature dependent property data available in the literature are spotty at best; some sort of tuning will always be required. This approach greatly reduces the cost of the FEA, uses a simple test procedure, and requires only a small material coupon. This procedure has been very useful for determining the model parameters.

LASER WELDING EXPERIMENTS

The 5000-watt CE5000/LPC8 $C0_2$ laser is a computer-controlled laser processing system comprised of a high voltage power supply, lasing chamber, and CNC workstation. The workstation is a five-axis machining center driven by an Allen Bradley 8400MP controller, which also controls the laser during program execution.

NSWCDDS laser is capable of delivering a beam of up to 5000 watts to the workstation. The beam is a continuous nonpulsed beam with a 3-inch annular mode; i.e., doughnut shaped. Once the beam reaches the workstation, it can be focused using one of two focusing heads.

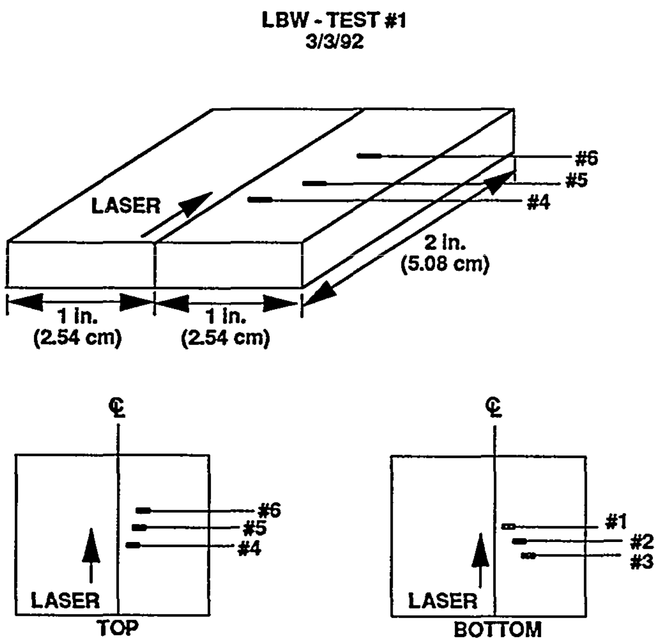
One of the focusing heads uses a conventional parabolic mirror, or a parabolic integrator mirror. The second focusing head contains a conventional parabolic mirror, which can scan up to a l-inch long line as fast as 20,000 cycles per minute.

The scanning focusing head is used for surface heat treating or cladding. In this use, a focused beam of 1.524-mm (0.06 -in.) diameter is rapidly scanned or dithered at a controlled rate as the part is moved under the laser head.

The other focusing head is used with the solid parabolic mirror for welding or cutting. With this mirror, the beam can be focused to a diameter of 1.524 mm (0.06-in.). The integrator mirror is a sectioned parabolic mirror with each section focused such that a 1%-inch square region is affected by the beam. The integrator mirror can be used for surface heat treating.

Laser machining is a noncontact type of processing; therefore, all setup fixtures are mostly used for positioning the parts under the laser, and for limiting movement of the parts due to thermal stress. The fixtures used are designed to assure repeatability of welding parameters.

All samples were made from %-inch 4340 steel sheets. The thermocouples used were OMEGA Chromel/Alumel ™with a 0.127-mm (0.005-in.) diameter. The laser spot test used seven thermocouples spot welded to the plate as shown in Figure 7. The welding experiment used the configuration shown in Figure 8 (only one plate contained thermocouples). In both experiments, grooves of 0.127-mm (0.005 in.) were machined into the surface of the plate steel. The grooves were aligned such that one end of the groove could be used when locating the thermocouples.



WELDING PARAMETERS:
LASER POWER = 70% (3.5 kW)
WELDING SPEED = 70 ipm 2.963 cm/s)
AMBIENT TEMPERATURE = 70 F (21.1C)
PLATE MATERIAL = 4130 STEEL (INITIALLY ANNEALED)
PLATE THICKNESS = 1/8 in. (3.175 mm)

THERMOCOUPLE	DISTANCE FROM ℄ (mm)
1	1.52
2	2.27
3	3.20
4	1.02
5	2.03
6	3.05

Figure 8. Welding experiment configuration

The spot weld experiment was the simplest way to show that the experimental data and the classical/FEMs approximated each other. As explained above, the spot heating experiment can be used to obtain average material properties for finite element analyses. In this experiment, a beam of 500 watts was focused on the sample for 1 second. The test was repeated using 2- and 4-second intervals. A Data 6000 Digital tape drive was used to record all thermocouples. An analog-to-digital converter with a radio frequency (RF) filter was used in line with the thermocouples.

In the welding experiments, the focused laser beam was used to weld two plates together while recording temperatures. The laser beam was started when the plate was well away from the sample, then the plate was moved at a constant feed rate in a line that tracked the seam. The laser shut off once the beam moved off the sample. Starting and stopping the laser away from the sample assures that there is a constant beam power during welding. Beam powers of 2000 to 3500 watts with machine speeds of 50 to 70 inches per minute were used in these experiments. Figure 9 shows the results of one of the experiments.

The plots on Figure 9 also show the Rosenthal analytical solution and the finite element solution. The Rosenthal solution is readily computed for the exact thermocouple locations and shows good agreement with the experimental data. The finite element results need further explanation. These results show temperature-versus-time plots for finite element mesh points near the thermocouples, but not exactly at the thermocouple locations. For example, thermocouple location number 4 is on the top surface 1.0 mm (0.0394 in.) from the weld center line. The closest node is number 1437, which is 1.524 mm (0.06 in.) from the weld. The nearest node to the first thermocouple underneath is number 1409, which is 1.016 mm (0.04 in.) from the weld center line.

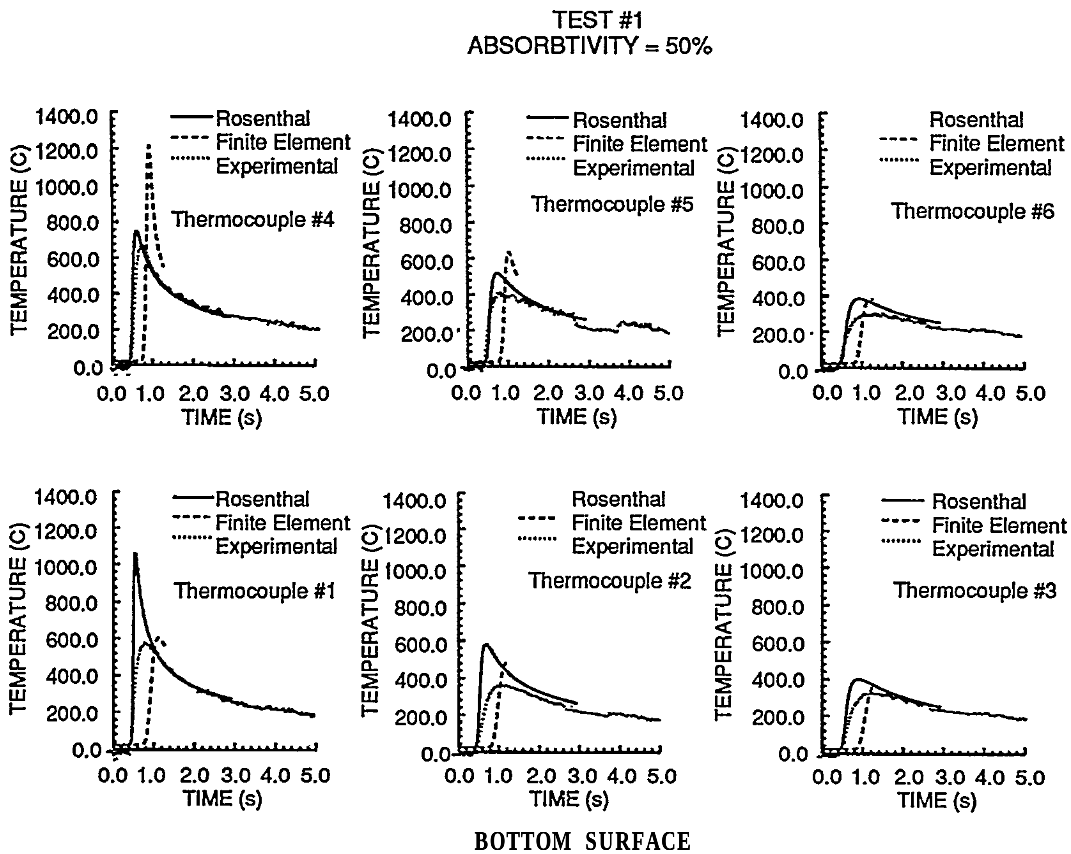


Figure 9. Temperature versus time plots from classical Rosenthal solution, finite element method, and experimental data

The Rosenthal solution does not take into account the variation of temperature with depth through the thickness of material. The heat source is from the top, so one would expect the Rosenthal solution to be higher than the bottom measurement close to the weld, and this is confirmed by the data. On the other hand, the finite element solution takes into account the heat flow in the thickness direction. The heating is from the top surface, hence, the high values in Figure 6 for location number 4, and much lower values for location number 1 on the bottom side. At the second location, a little over 2 mm (0.0788 in.) from the weld, the temperatures top and bottom are more nearly the same, as shown by curves 2 and 5. By the time the heat gets to the third location, the only difference in the two traces is a slower rise on the bottom side of the plate.

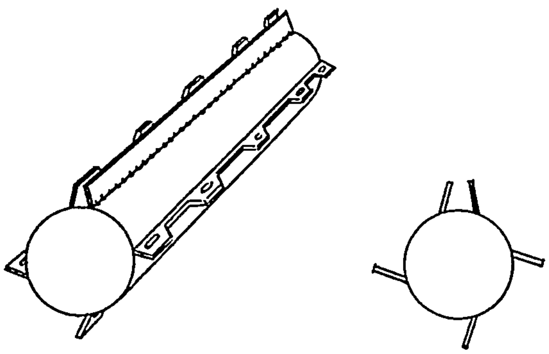
Another problem that occurs, especially close to the ~veld, is the thermocouples have mass and the leads are a heat sink, lowering the apparent temperatures. This is particularly true where gradients are strong and the transients are fast.

Finally, the general time phase different in the finite element results is due to a time base shift, not computational error.

After the experiments were performed, weld samples were sectioned and examined. The samples were polished and then etched using a 2-percent solution of nitric acid. The sample sections were examined for microstructure and microhardness. From microstructure photographs, the sizes of the actual weld melt zones and the heat affected zones were compared to the predicted analytical and finite element modeling, with good results.

FUTURE APPLICATIONS

The laboratory is presently pursuing three potential applications of the laser welding technology. The first application, nicknamed "Strip Clip"[2] (Figure 10), is an approach to building rocket motors (9). The second is a missile launching canister called the "Concentric Canister Launcher (Figure 11)." The third is the "Integral Ship-Weapon Module (Figure 12)."



ATTACHMENT OF LEFT FACING STRIP
MANUFACTURING PROCESS - 5

Figure 10. Strip Clip approach to laser welding

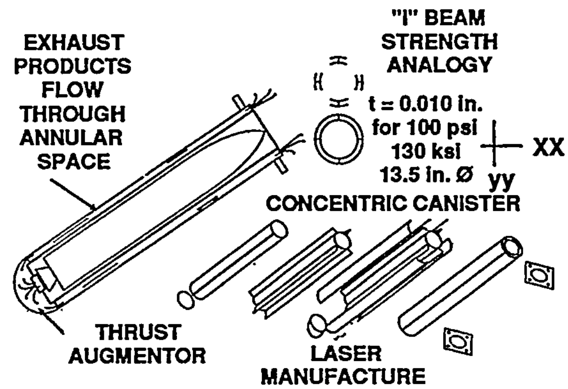


Figure 11. Concentric Canister Launcher approach

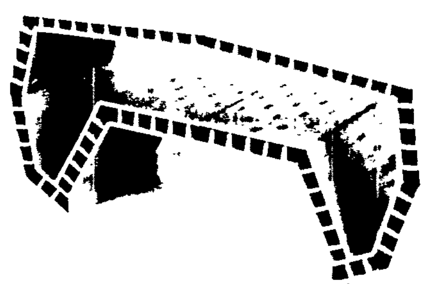


Figure 12. Laser-welded integral ship-weapon module

The present method of attaching the dorsal fins to the MK 104 rocket motor is by means of bolts passing through discrete fin clips. The "U" shaped clips, 216 per rocket motor, are presently welded to the chamber using 432 manual TIG welds on a preheated chamber. With laser welding, eight continuous strips are laser welded to the chamber on a CNC workstation. Only eight welds at ambient temperature are required on each chamber, Figure 10. The strips are then contoured and perforated by the laser in a cutting mode. Once set up, a complete set of attachments could be produced in only 20 minutes on a workstation, as opposed to the manual method that takes approximately two man days of manual welding.

The concentric canister launcher concept is shown by Figure 11. The concept was motivated by the Strip Clip rocket motor. The missile is fired from the inner cylinder or barrel. The inner cylinder supports the missile in handling and stowage, and guides it in initial flight. The missile exhaust flows into a hemispherical cup and is turned through 180 degrees along the axis of flight. The exhaust then flows in the annular space between the two cylinders. The same basic stress analysis approach is used as in the design of a rocket motor chamber. The manufacturing process is very close to the Strip Clip process, with the additional requirement to attach the outer cylinder. This can be done with petals, as shown in Figure 11, or by welding from the outside of a continuous cylinder, as explained below—using petals makes it easier to apply insulation to the annular space.

The integral ship weapon module is a concept for installing weapons in future surface combatants. The intent is to provide a fully stressed ship module for launching weapons. The weapon launcher becomes a structural part of the ship, rather than a plug-in item that fits through a heavily reinforced opening in the deck. The goal is to save weight, cost, and volume, thereby allowing a smaller, lighter ship with the same firepower as conventional designs. A ship module, of surface effect ship configuration, is shown in Figure 12. The model was built for demonstrating the welding and design approach. The design is a double hull with all plate construction. Plates are natural structures for finite element design. Virtually every finite element computer program has sophisticated and accurate plate elements. The laser welding process allows all the welding of the ribs to be done from outside the plate; i.e., the laser beam pierces through the plate from behind, then heats the rib, fusing it to the plate. The welding can be done continuously, as was done along the edges and at the center line, or intermittently, as along the ribs. Intermittent welds are obtained by turning the beam on and off while the parts are moving under the laser head. This process could also be used to attach the outer cylinder to the longer ones of the concentric cylinder launcher.

CONCLUSION

The rudiments of a "seamless engineering" process for design and production of laser welded structures have been demonstrated. Classical and finite element computer solutions of heating, cooling, and microstructure have been carried out. The calculations have been done in numerical databases that can also be used for stress analysis, printing out drawings, and development of CNC tool paths. Experiments, micrographs, and microhardness measurements have confirmed the computer methods. Several promising applications in the area of weapons, launchers, and shipbuilding were discussed.

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